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Phase I: FY01 Investigative Study for the Advanced Volume Sensor

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14. ABSTRACT

This report presents an overview of relevant resesarch and commercially available products as of FY01 that utilize spatial and spectral methods for fire detection systems. New capabilities are desired that can monitor damage control events in an entire space at a minimal cost. Optical detection methods are being investigated because this technology offers an effective means to monitor the entire space or volume without relying on diffusion of effluents to point sensors. Pattern recognition methods of video camera images (machine vision: spatially resolved) and spectrally resolved detection methods are being investigated for a volume sensor. Acoustic detection methods are also being considered and would be attractive for events such as flooding or pipe rupture. This is the first phase of the Advanced Volume Sensor task in the Future Naval Capabilities ONR program Advanced Damage Countermeasures. Several technologies are identified as having potential in the volume sensor development effort. The resulting system is expected to provide sensitive and selective detection of damage control events including fire.

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FY01 INVESTIGATIVE STUDY FOR THE ADVANCED VOLUME SENSOR

1.0 BACKGROUND

Under the U.S. Navy program Damage Control-Automation for Reduced Manning (DC-ARM), an early warning fire detection system was developed by processing the output from sensors that measure different parameters of a developing fire with a neural network pattern recognition technique. A key element to this objective was the improvement of current fire detection systems so that fire detection systems can be integrated with remote, automatic fire suppression systems. The use of multi-criteria based detection technology offered the most promising means to achieve both improved sensitivity to real fires and reduced susceptibility to nuisance alarm sources. [1,2,3,4] The sensors that comprised the early warning fire detection system are considered point sensors, i.e. the effluents from an event must diffuse to the sensor array where the event is identified.

Multi-criteria/multi-sensor approaches have been investigated with various degrees of success.[5,6,7,8] Few studies have provided results which clearly demonstrate the performance improvements of the new multi-criteria approaches compared to threshold-alarm smoke detectors.[9,10,11] In particular, most studies have not evaluated the nuisance source rejection capability of the new technologies. Additionally, tests demonstrating the improvements in fire detection sensitivity have been generally limited to a few standardized test sources (e.g., the EN 54 fire sources).

Recently, a sensor array system or electronic nose has become commercially available for indoor air monitoring and fire alarm.[12] This system, however, has not been optimized for the shipboard environment. Another electronic nose system under development elsewhere has recently been tested for fire detection applications.[13] Because of the lack of clearly defined improvements with available multi-sensor detectors[1] compared to smoke detection technologies, the U.S. Navy pursued this program to evaluate the potential advantages of developing a multi-criteria/multi-sensor detection system for the shipboard environment.

In the DC-ARM research program, a large database consisting of the responses of 20 sensors to several different types of fires and nuisance sources was generated in full-

scale laboratory testing and analyzed using a variety of multivariate methods.[14,15,16] The study identified the types of sensors that would be useful in a sensor array for early warning fire detection. Pattern recognition methods assisted in this effort by clustering fires and nuisance sources with similar response patterns and by identifying similarities between the sensors. Several different sensor combinations were identified for use with a probabilistic neural network (PNN) to discriminate between fires and nuisance sources. Using data from full-scale laboratory tests, improved fire recognition and low false alarm rates were achieved compared to commercial smoke detectors.[14,15,16] Full-scale shipboard tests were conducted on the ex-USS SHADWELL[17] to further develop detection algorithms and to expand the fire/nuisance source database.[18,19] Using the laboratory and shipboard data sets, candidate suites of sensors were identified for the development of a prototype multi-sensor fire detection system.[19]

The multi-sensor prototypes, Early Warning Fire Detection (EWFD) Systems, were evaluated in four full-scale shipboard test series. Test Series 1 tested the real-time responses of several prototype sensor combinations.[20,21,22] Two months later, under different environmental conditions, the prototypes were tested with more fire and nuisance sources in Test Series 2.[23] Test Series 1 and 2 results were then used to improve the prototype and select a final suite of sensors. The improved EWFD prototype system was evaluated in Test Series 3.[24,25] The results of these studies demonstrated the advantage of a PNN classifier with the multi-sensor, multi-criteria approach for fire detection. Test Series 4 was aimed at refining and improving the alarm algorithm based on the data and to develop a 14-unit prototype detection system that operated in real time. Test Series 4 was conducted to evaluate the implementation of the expanded alarm system and to evaluate various aspects of performance. Test Series 4 demonstrated improved performance of the current PNN alarm algorithm compared to previous prototype designs. The EWFD system demonstrated better overall performance than the commercial smoke detectors by providing both improved nuisance source immunity with generally equivalent or faster response times.

The EWFD system is a point detector and relies on diffusion of fire effluents to reach the sensors. For smoldering fires, the migration of smoke particles and fire by-products may be very slow. In addition, some nuisance sources emit fire like by-products

(i.e., welding and cutting steel with a torch). The EWFD system does not consistently discriminate these nuisance sources from real fires. New capabilities that can monitor the entire space or volume without relying on diffusion and can provide enhanced nuisance source rejection are desired.

One task in the current Navy Program, Advanced Damage Countermeasures, is aimed at developing an Advanced Volume Sensor. The ability to monitor the entire space can be accomplished in two ways. One is through networking large numbers of conventional sensors or point detectors and the other uses optical or acoustic methods. There are several problems associated with networking large numbers of point detectors. Currently the detectors are too expensive and would have prohibitively high maintenance requirements. In the future, sensor arrays may be developed that are low cost and modular, reducing the overall maintenance. The goal of this Advanced Volume Sensor Program is to develop a detection system that can monitor an entire space at once without relying on diffusion to carry heat, gases or smoke to a conventional point detector. One approach in the Volume Detector Program is to develop the capability of remotely monitoring fire and other events in ship spaces by adopting, and where appropriate adapting, optical detection technology that primarily relies on spectral information. The most reliable route would be to use a mid-infrared camera, which could use both spectrally and spatially encoded information to identify fire or smoke. But mid-IR cameras are currently too costly to be practical, so two parallel efforts are underway: one using pattern recognition methods of video camera images (machine vision: spatially resolved) and the other emphasizing spectrally resolved detection methods. Advances in acoustic detection methods will also be investigated and considered.

2.0   OBJECTIVE

The objective of this study is to establish the state of the art of optical and acoustic methods for advanced volume detection. The focus of the study is to identify current research and available products to utilize in an affordable, real-time volume sensor for identification of shipboard conditions such as those characteristic of fire, explosions, pipe ruptures, flooding level, CB (or hazardous gases) and security monitoring of spaces. The goal for fire detection is to improve sensitivity and event

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discrimination above that of point sensor detectors and reduce false alarms. Optical methods using both spatial and spectral resolving capabilities are considered.

3.0 APPROACH

The literature search primarily consisted of identifying relevant reports and technical papers from the literature and direct contact with manufacturers and researchers. A summary and analysis of the state of the art was developed based on a review.

4.0 SUMMARY OF THE STATE OF THE ART

4.1 Machine Vision Fire Detection

The basic concept of machine vision is to replace the need for human visual inspection or monitoring by utilizing video or photographic images with computer processing schemes to extract desired information. Once an image is obtained and digitized for computer input, the image is processed to extract key features and then these features are analyzed for specific information. Machine vision is a technology that is used in production/process industries, for monitoring production and quality control. In these situations, the image is quite constant throughout time except for the case when an abnormality is detected, which is the case the system is designed to identify. With a fire detection system, the video image is subject to many more variations due to normal operations of people, equipment, and ambient conditions within the field of view of the camera. Primarily over the past two decades, investigators started to evaluate whether machine vision could be used for identifying fires. The following section discusses some of the relevant work found in the literature and assesses the current state of the art.

In the late 1980s the Air Force had become concerned that typical smoke and heat detectors were too slow for proper fire protection of certain facilities and that optical fire detectors at that time were not accurate enough to preclude costly false alarms and activation of suppression systems. The Air Force initiated several projects to evaluate the feasibility of developing machine vision fire detection systems.

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Neal et al. (1991) conducted a proof-of-concept study to develop a neural network-based machine vision interface for detecting flame signatures in the visible spectrum.[26] The goal was to detect and classify fires in the presence of complex background images. The basic concept was to use machine vision techniques to generate digitally filtered HSI-formatted video data (HSI = Hue, Saturation , Intensity), filter the extracted information, and then use a neural network for fire analysis. The three main subsystems were 1) image capture, 2) image processing and 3) neural network analysis. The image capture subsystem extracted hue, saturation and intensity (HSI) elements of the image to form a color video image. RGB (red, blue, green) video format was also available, however, it was stated that HSI simplifies processing and the interpretation of fire region characteristics. The image processing substytem eliminated all parts of the image that did not have the intensity, hue and growth characteristics of fire. Lastly, the neural network subsystem compared the hue and saturation patterns of the remaining image to those of a training set of fire patterns. The investigators first attempted to develop mathematical models for fire classification, but this method proved to be difficult and inaccurate. They then turned to the use of a counter-propagation uni-flow neural network.

The machine vision system was slower than conventional optical fire detectors. At the time, the investigators stated that if the processing was implemented in computer hardware, the system would respond in less than 5 seconds. An experimental evaluation of a prototype system was performed. A training set of 137 scenarios (96 fire and 41 false alarms) was generated. The system was then evaluated using 23 validation tests (17 fire and 6 nuisance). The flaming fires included JP-4, wood, paper, butane, and Plexiglas. The false alarm sources included direct sunlight, reflected sunlight from glass, reflected sunlight from metal, reflected sunlight from wood and indoor lights. The neural network was reported to be 100% accurate for all training and validation cases. No detail of the tests was presented in the report. At the time of report, an expected prototype for further work was estimated to cost less than $10,000.

The machine vision fire detection work by Donmar also developed out of a project for the Air Force in which Donmar evaluated optical fire detectors and false alarm sources.[27,28] This work too occurred primarily in the early to mid 1990's with no further

published work since. Air Force affiliates stated that the machine vision fire detection work of the early 1990s never met the performance objectives that it should have to be a viable device. The available computer processing at the time was a limitation to the systems.

Other articles that appear in the literature also provide information of initial investigations of the use of machine vision for fire detection; however, until the last few years, none clearly presented a validated case for an operational system. So et al. (1994) used a 1024 x 1024 pixel resolution frame grabber and a black-and-white close circuit TV (CCTV) camera with a 386 PC for processing.[29] Images were typically obtained once a minute. However, if an image was analyzed and a fire condition suspected, the system sample rate was increased to 1 image per second. This system compared frame pixels at different time steps to determine a change in the field of view. Images were represented using histograms of the number of pixels that fall within the measured value of 0 to 255, divided into increments of 25. Features were extracted from the image using a fuzzy set membership function based on the pixel count histogram values. The algorithm identified three classes: background, intruder, and fire.

The researchers used optical flow analysis to discriminate between intruders and smoke/fire conditions. Optical flow analysis evaluates the velocity field that is generated in the images due to an object moving, i.e., an intruder or smoke from a fire. So et al. concluded that their computer-based security and fire-detection system was not suitable to totally replace conventional detection systems. However, it provided a basis to improve response and was able to accurately identify incipient fires. The system was fully automatic and was stated to be most applicable to unmanned buildings. The authors did not present any evidence of the level of effectiveness. No experimental data was presented to demonstrate the fire detection performance capabilities.

Plumb and Richards of Washington State University received a grant from the National Institute of Standards and Technology (NIST) titled, "Development of an Economical Video Based Fire Detection and Location System."[30,31,32,33] The work under the grant was completed by the mid 1990s. The video fire detection system consisted of a black and white video camera that monitors passive sensors (i.e., temperature sensitive sheets) attached in a symmetrical arrangement on the ceiling. The sensors change color

at a prescribed temperature between 30 to 40°C. A frame grabber that digitized the video image translated the image to a 486 computer, which processed the image to determine sensor activation. An inverse problem solution was used to estimate the size and location of the fire. This system was experimentally evaluated on a small-scale basis (5 m x 2.75 m x 1.5 m high space). Issues that were partially addressed included the ability of the system to view the sensors at low light levels and through smoke. The researchers noted that the work performed was not proof that the system was ready for full-scale implementation but rather that it presented a proof of concept.

The Washington State system has the advantage of providing fire detection as well as location and size information of the fire. The investigators claim that the system was able to determine heat release rate to within 20% for most of the trials. However, the tests appear to have been done with limited sources, most with a 2.4 kW camp stove as a flame source. The ability of the system to locate the camp stove fire was stated to be within in one half of the sensor-to-sensor spacing (sensors were spaced 1 m apart). Increases in the heat release rate are reported to increase the error in the location and heat release rate determinations.

One disadvantage of the system is the reliance on needing multiple sensors installed in a grid work on the ceiling. In addition, the video system needs to be able to have a complete view of all sensors. The investigators did not discuss the sensitivity of the system to the view angle of the camera to the sensors. Particularly for overheads with beams, there may be logistical problems with implementing this system onboard a ship. More recent work by NIST is focusing on using other sensor information obtained from smoke detectors and alternate temperature measurements along with inverse solution methods to obtain the fire size and location information.[34]

Cheng et al. (1999) discuss a video fire detection system that was developed prior to 1998.[35] The investigators used a liquid crystal light valve (LCLV) in front of the lens of a charge coupled device (CCD) camera to aid in the discrimination of flames from background illumination. The LCLV either allows both visible and infrared light to reach the CCD sensor or only infrared light. When the visible light was filtered, the flame was more easily recognizable. Cheng reports that the LCLV can be electronically controlled

so that it can be easily and quickly switched between modes to allow normal video imaging and fire monitoring.

The authors do not provide the details of the criteria used to discriminate fires from other hot objects. They present several image characteristics that may be used. These characteristics include the rate of increase in the number of flame image pixels (representative of fire growth), fluctuations in the image related to the fire, movement of the image related to fire spread and the shape of the fire. Cheng et al. report that a system was developed in the early 1990s and one was installed in a department store in 1995. Another system was installed to monitor a power cable tunnel of an iron and steel factory. The fire detection and the security monitoring modes used 1-2 frames per second with monitor resolution of 640 x 480 pixels. The authors state that the technology is suitable for detection in large spaces or inhospitable environments. The system was designed so that if a fire is detected, the system will switch from the fire mode to a normal video image.

Foo (2000) used a fuzzy logic approach to detect hydrocarbon fires in aircraft dry bays and engine compartments.[36, 37] Using statistical measures of the histogram and image subtraction data of successive frames, fuzzy if-then rules were derived to determine the probability of a fire event. The fuzzy logic approach was tested for false alarms using flashlights and high-power halogen lights. Real fires were discriminated from light sources using a combination of histogram and image subtraction statistical data for the fuzzy system.

Vergara et al. (2000) describe a general scheme for automatic signal detection to monitor fire by infrared digital signal processing.[38] The method determines whether an alert situation exists in scanning surveillance systems. The signal is detected using a linear predictor and a subspace model in successive scans to maximize the performance of the detector. The authors demonstrated an improved probability of detection for uncontrolled forest fires while reducing the probability of detection for undesired events using a matched subspace approach.

Arrue et al. (2000) also developed an intelligent system for the false alarm reduction in infrared forest-fire detection.[39] The authors combine real-time infrared-image processing techniques and an artificial neural network with information from

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meteorological sensors. They take advantage of the information redundancy from visual and infrared cameras through a matching process. The decision function that predicts the fire probability used a fuzzy expert rule base method. An insufficient number of tests were conducted for a statistical study. However, the study indicated a dramatic decrease in false alarm, while maintaining the detection capabilities.

4.1.1 Smart Fire Alert

Fastcom Technology is a relatively new company in Switzerland, established in 1998, working primarily in the field of embedded signal processing systems for various industries. The company has recently distributed preliminary informational brochures for a CCTV video fire and smoke detection system called Smart Fire Alert. The system is currently being targeted toward tunnel surveillance and large indoor facilities, such as power plants. A system has been tested in a tunnel and was briefly presented as working successfully during a presentation at the Twelfth International Conference on Automatic Fire Detection.[40] One system has been operating for one and half years in a large space of a nuclear research facility.

The Smart Fire Alert system uses up to four CCTV cameras and software-based algorithms that run on PC platforms. The algorithms use current image processing technology with various analysis criteria, such as movement and fire color. The algorithms are rule-based with some elements of fuzzy logic. The system is capable of detecting both flaming and smoldering fire sources. As the system has not yet entered the market and is still being evaluated, it is difficult to fully assess the fire detection performance. Fastcom Technology states that the system has been shown to be faster than linear heat detection systems in tunnels, responding 20 to 30 seconds faster with the camera spaced 60 to 80 m from the source. The company is primarily marketing the technology for large indoor spaces. The use of this technology in smaller spaces, as would occur onboard ship, needs to be demonstrated; though, the company reports that the system should operate well in typical sized rooms.

4.1.2 VSD-8 Video Smoke Detection System

Intelsec Systems Limited (ISL) has developed a relationship with Fire Sentry to market the video smoke detection system called VSD-8. The VSD-8 is representative of the leading machine vision technology that is commercially available today. This system uses standard closed circuit television (CCTV) equipment with a self contained processing system to identify small amounts of smoke within a video image. The VSD-8 is designed to detect smoke only. Work is on-going to develop a system that can also detect flames.

The processing system is a customized Black Box containing a PC and digitizer. Via proprietary algorithms, the system is able to process video information from up to eight cameras simultaneously. Smoke is detected in the video image by identifying areas of change within the image. The pixels showing the change are analyzed further according to a series of filters identifying particular characteristics associated with smoke. Based on the analysis, the system determines whether the video image is smoke and whether a sufficient smoke level is present to signal an alarm. Parameters, such as smoke level, duration of time, and area of the space analyzed within a camera view, can be adjusted to tailor the system to an application. Multiple algorithms are used to properly classify smoke related to fires and to discriminate against false alarm sources, such as steam. The algorithms evaluate different features of the images, including edge evidence, softness, compactness and density.

Currently, there are multiple systems installed in various applications, including nuclear facilities, power stations in the UK, warehouses, aircraft hangars, interior spaces of off-shore platforms and engine rooms of transport ferries. The manufacturer states that the system works well in areas of large spaces where point detection is inadequate, areas with large amounts of complex machinery, and outside areas. Situations to avoid according to the manufacturer are where background smoke levels are high (e.g., welding operations or excessive diesel smoke from forklifts – reasonable levels can be tolerated), low light levels, situations where the camera image may be obscured (e.g., viewing through a screen or frosted glass, …), or where lighting conditions are likely to cause camera flare. If steam is a continuous part of background the system can distinguish

between this and smoke. There is limited ability to distinguish between bursts of steam and smoke.

The VSD-8 can operate in low light levels. If levels are very low (e.g., less than 4 feet visibility) an IR sensitive camera is needed. The IR sensitive cameras are approximately $50 more than standard CCD cameras. As long as one can see across a room, a standard camera would be suitable. Turning off the lights in a space would cause an alarm condition with the current programming of the system.

Fire Sentry reports that areas of future work include the development of a flame identification algorithm, the ability to expand the system beyond 8 cameras, and the implementation of new capture cards. The new capture cards will allow 80 percent of the image processing to be performed at the device level.

Limited data is available to evaluate the performance of the VSD-8 system. Promotional videos were reviewed that demonstrated the system quickly detecting low levels of smoke in a power plant before the smoke was distinctly visible in the video image. Tests of the system also showed the VSD-8 responding faster to standard European smoke detector test sources (EN54 tests) than conventional smoke detectors. The limited data makes it difficult to fully assess the performance capabilities of the VSD-8 system. It is uncertain whether the smaller spaces on a ship would present a technical difficulty, since the system is primarily used in large open spaces. None-the-less, the VSD-8 system demonstrates that machine vision technology has improved to the point that smoke detection is possible.

4.2   Spectrally Based Volume Sensor Fire and Smoke Detector

The spectrally resolved optical approach attempts to exploit the fact that emitted radiation, particularly in the mid infrared region, is a sensitive indicator of the presence of gases produced by fire (such as CO and CO_2) and of elevated temperature (such as indicated by the black body radiation emitted by hot objects including soot). The optical detector in this case involves a single (or few) element(s) with a wide field of view that can remotely detect changes throughout the compartment such as those that accompany the outbreak of fire. The wavelengths detected are chosen to increase sensitivity and minimize false alarms and often operate in the IR or UV, both (UV/IR) or several at different IR wavelengths. Some commercial detectors use a combination of UV, IR and visible band sensors, while others use dual or triple IR sensors.

Beam smoke detectors are another way to monitor a large area. In these smoke detectors, a light beam (visible or near IR) is sent across the space and smoke is detected by its obscuration, or its effect of reducing the transmission of the light beam. These devices consist of two parts, a source and a detector (or a source/detector and a reflector). This kind of smoke detector is less common than conventional spot smoke detectors, which are most prevalent as photoelectric (light scattering) or ionization types.

The Volume Sensor is expected to combine an optical fire and/or smoke detector (OFSD) capable of remote sensing with previously developed and demonstrated conventional point detectors using current neural networking capabilities in order to produce a multi-sensor, multi-signature device that provides high sensitivity and few false alarms.

Optical fire detectors (OFD) and/or beam smoke detectors are available from a variety of sources. A list of some vendors of each are provided in Table 1. For shipboard applications, COTS systems will be evaluated and modified from the commercially available designs as required. Few multisensor, multicriteria fire detection systems have included optical detectors in combination with conventional smoke detectors and the former could provide independent input that could improve the capabilities of a composite device relying on signal processing.

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Table 1. Manufacturers of Optical Fire Detectors or Beam Smoke Detectors

OFD	Beam Smoke Detector
Spectrex	Simplex
Detectronics	Cerberus (Siemens)
Meggitt Avionics	System Sensor (GE)
Fire Sentry	EST
	Notifier (View)
	Fire Control
	Hochiki
	Esl - Sentrol

The operating principles for OFD are nicely summarized on the Spectrex homepage (www.spectrex-inc.com). The spectral emission of fires are shown along with those of common nuisances, such as the sun, non-fire heat, lamps and arcs. Detection wavelengths are chosen for high sensitivity and specificity. The primary IR band monitored is the CO_2 band at 4.3 mm; if IR is used this is the first wavelength chosen. When UV radiation is detected, the band is 180-280 nm. (The short wavelength edge corresponds to the edge of atmospheric transmission.) A second or third IR wavelength is typically away from a strong emission band (e.g., 4 and 5 mm) and used to ratio to the 4.3 mm band to discriminate against nuisances. Some of the COTS detectors also use some time dependent signal criteria such as flicker rate or signal rise time, as well as absolute signal levels for identifying a fire condition.

A study was recently reported by Gottuk et al. on OFD performance in aircraft hangars in which it was found triple IR detectors were more effective than units using UV/IR and dual IR.[41] (Spectrex and Detronics are the only vendors who currently offer triple IR detectors.)   This provided evidence that the previous Navy regulation stipulating that hangar fire detection use only UV/IR was unwarranted. The current practice in Navy hangar design is to use triple IR optical fire detection. OFDs are effective at monitoring a wide area, but they are primarily flame detectors and not very sensitive to smoldering fires. Another limitation is that they are line-of-sight detectors so that they would not respond quickly to an obscured event. For this reason, the Volume Sensor may benefit from including a beam smoke detector and/or a photoelectric point smoke detector. (In terms of commercial smoke detectors, photoelectric detectors are known to be more sensitive to smoldering fires than ionization detectors.)

There are several reports that summarize beam and point smoke detectors.[42,43,44,45] Loept et al. (1997) discuss the particle characteristics of fire and non-fire sources and describe various strategies for enhancing smoke detection sensitivity and specificity.[46] The latter includes parameters of light scattering such as scattering angle, polarization and wavelength dependencies. For example, using the polarization dependence was not found to provide a reliable way of distinguishing smoke from other particulate. Beam smoke detectors suffer from some of the same limitations of optical fire detectors, such as being line of sight. Also, hangar fire tests have been reported in which fires completely obscured beam smoke detectors so that they registered a fault rather than alarm until the sensitivity was lowered below the level recommended by the vendor.[47] In the event that COTS beam smoke detectors are inadequate, an improved approach may be to combine elements of the photoelectric detectors with a beam system. There are ways to improve the sensitivity for smoke particles, which are typically 0.1-10 microns in diameter. These include using short wavelength light, where scattering is stronger, and using several wavelengths as a way to discriminate various kinds of particles.[45] For example, a smoke detector design for use by the Air Force for spacecraft was based on a two color UV beam detector approach.[48] It may be possible to achieve wide area coverage and sensitivity using forward scattering for a projected beam with a slightly off-axis detector, several detectors at higher angles or multiple wavelengths. It may be possible to expand the coverage of a projected beam system with a scanning light source. Beam systems were tested in the DC-ARM program and demonstrated their usefulness in an array.[15,18]

It may be economical to use a near infrared camera. There have been reports of using near infrared detection at two wavelengths (900 and 1000nm) to determine source temperatures.[49] Nightvision cameras can be quite cheap, and although typically not as informative as mid infrared, they may provide a thermal imaging capability, albeit one that may be fainter than would be seen in the mid infrared. This method has been used in detecting forest fires from near infrared cameras.[50] There have been open path FTIR instruments used to monitor or characterize fire and smoke.[51] Similarly, there are reports[52] of using tunable diode laser absorption spectroscopy to monitor relevant gas phase species by using narrow absorption features. These methods are probably too expensive and complicated to use as a long term, maintenance-free OFSD. In the work

by ORBITEC, the camera used was the Texas Instruments Nightsight (8-14 mm) and was listed as costing only $8000. It appears to have much more capability than required for reliable fire detection, so that it would be worthwhile to consider finding a inexpensive, mid-IR camera for fire detection by infrared machine vision.

4.2.1 ORBITEC – Orbital Technologies Corporation

ORBITEC has developed a method for fire detection in aircraft hangers called Infrared Fire Detection and Alarm (IRFDA) System. IRFDA uses a unique pixel-count frequency spectrum of an IR camera to define a source as a fire or nuisance. Testing by the Air Force has shown that the IRFDA System is more reliable than any system previously tested.

4.3 Acoustic Detection

In addition to the standard optical approaches, OFD and beam smoke detectors, there are some unconventional approaches that could yield successful remote detection of fire and smoke. Acoustic detection has been reported with limited success [53] and this approach might warrant some attention (the development would be in recognizing acoustic signatures of fires and discriminating them from background and nuisances – machine hearing). A number of studies have investigated the possible use of acoustics for fire detection. Many of these studies have focused on the use of special sound generating materials as the means for creating a specific sound during a fire; monitoring for the acoustic signature would indicate a fire condition. In some cases the sound generating materials would not be special additives but rather standard building structural components, such as wood studs within a wall. Generally the literature only includes preliminary, investigative work on the feasibility of the concept of acoustic detection of fires; in a few cases, concept designs have been presented. The following section provides a brief review of specific studies related to acoustic fire detection.

Pietersen investigated the use of small freon-filled micro-capsules (small enough to be put into a coating) as a sound source to be detected by a crystal microphone (Acoustic Micro-Capsule Burst Detector).[54] Bursting micro-capsules have a characteristic noise that can be discriminated from ambient sound in a room. The capsules are designed

to burst only when a fire occurs. One limitation that would need to be further investigated is that the micro-capsule bursting/sensing frequency of 11 kHz also contains many natural sounds especially in home environments and onboard ships. The audible range is between 20 to 20,000 Hz. Schechter showed that sounds from frying bacon, frying eggs, television inter-station hiss ("snow") created significant sound levels at 11 kHz.[55]

In an attempt to create a detector of high frequencies, away from the natural and man-made noise spectrum, Schechter used a high frequency acoustic sensor to detect high frequency energy during dehydration of hydrated chemicals.[55] By finding a chemical that emits a unique high frequency sound when heated, a frequency detector could be tuned to identify this unique sound and, thus, indicate a fire when present. Schechter identified a range of 31 to 33 kHz as a potentially useful range with little interference from the acoustic environment. Isolated chemicals were evaluated. However, further work would need to be completed to determine how the chemicals would react when mixed into other materials, such as paint to be used on the overhead or bulkheads of a ship space. The combination of materials will lead to different sound characteristics. A specific chemical capable of emitting a unique high frequency sound (far removed from nuisance frequencies) that was also suitable to be included in fabrics, paints, etc. was not identified.

Detriche and Lanore studied the detection of low sonic and subsonic frequencies (up to 2 Hz) generated from combustion.[56] Their limited study evaluated the sound produced from ethyl alcohol pan fires as measured at different distances from the source. The investigators state that the acoustic emission spectrum of the fire peaks at a frequency characteristic of the diameter of the seat of the fire. They also stated that considering that background noise levels vary widely, determining a detection limit would be difficult and likely site-specific. With the state of the art in 1980, the investigators believed the use of these low frequency signals for fire detection would be extremely difficult due to the signal strength. The acoustic signals decayed rapidly with distance (a 10 dB decay was observed when the distance from the fire to the microphone doubled).

Other investigators studied the detection of fire via measuring acoustic emission from hidden structural members.[53,57,58] Piezoelectric transducers were mounted directly to structural materials (e.g., joists and wall studs) to record ultrasonic events in the materials resulting from a change in stress (thermal stress from a fire) that generates an elastic wave. Apart from fire detection, acoustic emission (AE) has been used to characterize fracture mechanisms and locate defects in structures. AE is widely used in non-destructive evaluation of materials and process monitoring related to welding, drilling, soldering, bonding and riveting procedures that put materials under stress and stimulate cracking and crack growth. Additional applications of AE include field-testing aerospace structures and bridges, above and below ground leak testing, and advance composite testing.

The study by Grosshandler et al. demonstrated that fires can be detected using AE and the method may respond faster than conventional fire detectors for concealed smoldering fires.[53,58] However, the researchers state that there is still much work to be done to fully develop a practical system. Signal-to-Noise ratio is problematic (no effort was made to isolate the experiments from background noise). If an object would fall on / collide directly with the beam being monitored, the resulting strong [acoustic] emissions would be detected by the sensors. However, the acoustic emissions sensors could be trained to ignore isolated high energy events/sounds (human voice, movement in room, exhaust fans, doors opening/closing, telephones…) while still identifying the number of acoustic emissions that would indicate a fire. The investigators also point out limited area coverage and possible high cost and maintenance as potential limitations for using acoustic emission for fire detection. Advanced acoustic emission data analysis pattern recognition and neural networks software is now commercially available, which was not available when the research was conducted. This new software, allows more sophisticated use of the acoustic emissions data and could lead to alarm algorithms with good discriminating capabilities between fire events and background and nuisance source events.

Redding proposed the use of sound beams for fire and gas detection.[59] The transit time for a beam of sound between fixed points (i.e., across a room) can be used to measure gas and temperature in the path. The velocity of sound is specific for each liquid

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and gas and varies with temperature. An array of transmitters and receivers for the sound beams is necessary since it detects a difference in patterns between adjacent sound beams. Redding states that ambient changes in temperature, pressure, and humidity change the transit time for all the sound beams in a space, but a gas leak, hot air, or increase in energy at any point would disturb the pattern and be shown as a difference between adjacent beams. For detection, the system could monitor for both a peak value and a rate of change. Training of the system is required to discriminate between fire and nuisance sources (i.e. steam could cause an alarm, unless detector trained to ignore it).

Ditizio has proposed another acoustic technique called Bulkhead Acoustic Transceiver (BAT).[60] The technique is an active method that uses MEMS transducers, phased array mapping, and signal processing that gives flexibility for applications. It is proposed that this method will be able to detect smoke and thermal gradients, recognize machinery vibration signatures, and provide personal monitoring.

Another task in the Advanced Damage Countermeasures program Henry Whitesel will investigate **Automated Hull Damage and Stability Monitoring.** This effort will develop a monitoring system that will automatically sense structural defects and flooding status, calculate and predict stability condition, and recommend and initiate actions as appropriate. The rupture and detection and instrumentation will include ultrasonic sensors for hull rupture and defects. It may be possible to use these sensors or similar sensors for acoustic monitoring of events.

As indicated in the literature reviewed, the use of acoustic signatures for fire detection holds the potential for success but has not been extensively evaluated. For the development of a volume sensor, acoustic emissions provide a means to detect fires that are shielded from line of sight measurement techniques. The AE hardware currently available needs to be investigated for this application since most studies on this subject were conducted 10 to 20 years ago. The advancements in electronic equipment and microprocessing may present more opportunities in AE fire detection. Further evaluations of acoustic emissions from shipboard fire scenarios (particularly for high frequency components) may prove useful as a discriminating signature.

5.0   SUMMARY

Humans are the fire detectors used on most Navy ships. They are multi-sensory detection systems combining the sense of smell, sight, hearing, and touch with a very sophisticated neural network (the brain). The need for reduced manning on ships requires technology replace some of the functions currently achieved by the sailors. The DC-ARM program produced the Early Warning Fire Detection System. The EWFD system uses conventional sensors, such as ionization and photoelectric smoke detectors, and gas sensors processed with a probabilistic neural network. The multi-criteria system mimics the human nose and will be the starting point for the Volume Sensor. The Advanced Volume Sensor program will investigate alternative sensing methods. Two parallel efforts are underway for the development of a Volume Sensor. One uses pattern recognition methods of video camera images (machine vision: spatially resolved) and the other emphasizing spectrally resolved detection methods. The volume detection capability will be achieved by combining point sensors with optical detectors (machine vision), OFD and/or beam smoke detectors (and possible others such as acoustic) with signal processing achieved using a neural network. The Volume Sensor will be evaluated using fires and nuisance sources in the environment of ship spaces.

An overview of relevant research and available products for the development of Volume Sensor has been presented. This is a very active field of research and development with much success demonstrated for limited applications. The work has shown promise in providing a fast, reliable fire detection system using optical methods. More work is necessary to clearly demonstrate the performance capabilities, particularly with regard to Navy ships. These methods also have the potential to provide detection capabilities beyond fire detection. Some of the possible uses include detection of explosions, pipe ruptures, flooding level, Chemical/Biological detection (or hazardous gases) and security monitoring of spaces. Some applications will use an array of sensors representing a variety of sensing types, while some applications will only need a subset of the capabilities, i.e., camera with machine vision.

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